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Using photoluminescence (PL) excitation spectroscopy we measured trapping times and recombination times in stepped QW's and coupled QW's and related the results to the wavefunction/interface overlaps.
Continuous wave PL excitation spectra of multiple narrow-stepped QW's at room temperature have been measured for the first time. It has been observed that PL intensity increases stronger than as a square of the excitation intensity, and we have attributed this phenomenon to the intricate blend of the radiative recombination between free carriers with the nonradiative recombination on the saturable interface traps. Using the CW PL data only we have managed to measure both the trapping efficiency and ratio between electron and hole radiative and nonradiative decay times.
The result of this research were published in the two separate articles in the Applied Physics Letters [2,4,8] and presented at international conferences [11-13].

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MATERIAL ENGINEERING OF THE NOVEL SEMICONDUCTOR STRUCTURES

Submitted to:

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HIGHLIGHTS OF THE RESEARCH FROM Feb. 1992 to Feb. 1993

I. EXPERIMENTAL WORK

STUDY OF THE TRAP SATURATION IN MULTIPLE QUANTUM WELL STRUCTURES.

Using photoluminescence (PL) excitation spectroscopy we measured trapping times and recombination times in stepped QW"s and coupled QW's and related the results to the wavefunction/interface overlaps.

Continuous wave PL excitation spectra of multiple narrow-stepped QW's at room temperature have been measured for the first time. It has been observed that PL intensity increases stronger than as a square of the excitation intensity, and we have attributed this phenomenon to the intricate blend of the radiative recombination between free carriers with the nonradiative recombination on the saturable interface traps. Using the CW PL data only we have managed to measure both the trapping efficiency and ratio between electron and hole radiative and nonradiative decay times.

The results of this research were published in the two separate articles in the Applied Physics Letters [2,4,8] and presented at international conferences [11-13]

II. THEORETICAL/MODELING WORK

1. COULOMB ENHANCEMENT OF THE NONLINEARITIES

We analyzed the fundamental limits of the third-order nonlinearities in the mesoscopic structures and have found that the only way they can be increased is via many body interactions. The prospects for the enhancement of the third-order optical nonlinearity in the mesoscopic semiconductor structures: quantum wells, wires, an boxes were all analyzed. It was shown, that if the structures are designed is such a way that the ground state and the excited states wavefunctions are spatially separated, then the electrostatic Coulomb interactions will result in the enhancement of the optical nonlinearity The enhancement factor has been analyzed for the structures of different shapes and material compositions. It was found that the possible enhancement factor ranges from 2 for quantum wells to 10 for quantum wires and boxes.

We have also approached the many body interaction between the virtual carriers. Coulomb interaction between photoexcited virtual carriers or virtual excitons in two-

dimensional heterostructures has been theoretically considered using bare-states and dressed states approaches. It was shown that if the wavefunctions of ground and excited states are spatially separated, Coulomb interaction causes coherent pulsations of the transition energy. As a result, significant (an order of magnitude) enhancement of the dynamic Stark shift and other ultrafast nonlinearities can be achieved. The enhancement of ultrafast nonlinearities was evaluated as a function of the geometry, doping level, broadening and other parameters. The effect of Coulomb interaction on the coherent transient phenomena was considered. The problem of practical realization of the proposed effects was addressed.

The results of this investigation are reported in two refereed papers [1,6]

2 ELECTROABSORPTION IN TYPE II SUPERLATTICES

Electric field-dependence of the optical absorption in the $ZnSe_{0.35}Te_{0.65}$–ZnSe type II superlattice has been studied by us theoretically An extremely large blue shift of the absorption edge was found for the structure makes it an attractive choice for the waveguide visible light modulators.

We have also studied the electric field-dependence of the exciton absorption in the $ZnTe_{0.35}Te_{0.65}$–ZnSe type II superlattice and we have found that the exciton can be observed even at very strong electric field strength.. Large effective blue shift of the absorption edge and strong modulation of the absorption prove that type II structures can be used in the visible spatial light modulators and switches.

The results of this effort are reported in two Journal papers [3,5] and prsented at the International Conferences [9,10].

3. OPTICALLY-PUMPED INFRARED LASERS

We have shown that far-infrared lasers can be built based on multiple QW structures.

We proposed a new type of the low threshold optically-pumped far-infrared laser based on multiple QW structures. We analyzed the population dynamics and optical gain in the proposed structure and showed that optical gain of the order of few hundred cm^{-1} can be achieved at 77K. and somewhat smaller gain can be found at room temperature. In the process, we developed the computer model for the different processes influencing the relaxation processes pertinent to the laser operation: LO phonon scattering, ionized impurity scattering, electron-electron scattering etc.

Currently we have the structure itself grown and are planning to start experiments soon.

The results are reported in the chapter in the proceedings and in the Journal article.

4. TWO-PHOTON ABSORPTION AND NONLINEAR REFRACTIVE INDEX NEAR THE MID_GAP PF THE QUANTUM WELLS AND QUANTUM WIRES

Among all the nonlinear optical properties of the semiconductors the two-photon absorption (TPA) and associated with it nonlinear index of refraction (n_2) have always attracted substantial interest . Recent development of two-dimensional quantum well (QW) and one-dimensional quantum wire QWr systems have prompted the theoretical and experimental studies of TPA in those structures The theoretical papers are mostly concerned with the computer evaluation of the TPA for the specific QW systems, while not devoting enough attention to the TPA dependence on such parameters as material composition and size Also, no detailed comparison of the TPA in 1-D, 2-D and 3-D systems have been made.

In our study, the TPA in QW's and QWr's have been investigated theoretically using full treatment of the valence bands rather than simple one-band effective mass theory. Simple concise expressions for the TPA for various polarizations have been obtained. These expressions depend only on the wavelength of light, bandgap energy, quantization energy and the ratios of the effective masses.

sing these expressions, the shape and magnitude of the TPA can be estimated without resorting to lengthy computer calculations. Ee have shown theoretically that in the limit of very wide QW's and QWr's their TPA becomes identical to that of bulk semiconductor. This result could not have been obtained unless the complete valence band model

had been used.

We have also evaluated the real part of two-photon susceptibility - n_2 and have shown that in QW's and QWr's near the TPA edge, the ratio n_2/β is larger than in bulk semiconductor - and, therefore, more efficient nonlinear devices can be built using QW's and QWr's.

The results of this work have been reported at CLEO-93 conference and are submitted to the Journal of Optical Society B

5. INTERSUBBAND TWO-PHOTON ABSORPTION AND NONLINEAR INDEX OF REFRACTION IN QUANTUM WELLS.

We have developed a simple theory for the two-photon intersubband absorption and associated with it nonlinear refraction in the multiple quantum wells (QW's) is developed. Using it, the third order nonlinear susceptibility is evaluated for the QW's of different shapes. We have shown that $\chi^{(3)}$ of as much as 10^{-7} esu can be achieved below the two-photon resonance where the absorption is small. Thus it is preferable to use multiple QW's as in nonlinear devices at frequencies less than half of the intersubband frequency.

In order to expand the useful wavelength range, we have also considerd the two-photon transitions from the the confined states to the continuum in the semiconductor quantum wells and superlattices Both two-photon absorption coefficient and the third order nonlinear susceptibility related to it were calculated. The results show that the nonlinear index of refraction as large as $10^{-9}cm^2/W$ can be achieved in the important 10 μm region where the absorption is small, opening a possibility of operating nonlinear optical devices in the far infrared domain.

Finally, we have anayzed the strengths of the intersubband and band-to-band transitions in quantum wells are compared using simple $\mathbf{k}\cdot\mathbf{p}$ analysis, and, contrary to the prevalent opinion, found to be nearly equal. The implications for the design of detectors and nonlinear optical devices are considered.

The results of the work were reported in three journal publications [7] and presented at the conferences [14]

LIST OF PUBLICATIONS IN THE COVERED PERIOD

JOURNAL PUBLICATIONS

1. J. Khurgin, "Coulomb enhancement of ultrafast nonlinearities in quantum wells", J. Opt. Soc. Am. **B, 9,** 157, (1992)

2. Y. J. Ding, C. L. Guo, J. B. Khurgin, S. Li, K-K Law, and J. Merz, Continuous photoluminescence excitation spectra of multiple stepped quantum wells: evidence for saturation of interface traps., Appl. Phys. Lett., **60,** 154, (1992)

3. S. Li, J. B. Khurgin, "Electroabsorption in type II multiple quantum well structures", Appl. Phys. Lett., **60,** 1969, (1992)

4.Y. J. Ding, C. L. Guo, J. B. Khurgin, K-K Law, and J. Merz "The diagnostics of recombination processes in multiple asymmetric coupled quantum wells by means of observation of continuous photoluminescence saturation", Appl. Phys. Lett., **60,** 2051, (1992)

5. S. Li and J. B. Khurgin, "Excitonic Electroabsorption in type II superlattice", Appl. Phys. Lett., **61,** 1694, (1992)

6. S. Li, and J. Khurgin, "Longitudinal Coulomb Attraction in Coupled Quantum Wells" PR, **B46,** 12535, (1992)

7. J. Khurgin and S. Li "Two photon absorption and nonresonant nonlinear index of refraction in the intersubband transitions in the quantum wells", Appl. Phys. Lett., **62,** 126, (1993)

8. Y. J. Ding, C. L. Guo, J. B. Khurgin, K.-K. Law, and J. L. Merz, in multiple narrow slightly asymmetric coupled quantum wells," J. Opt. Soc. Am. **B, 10,** 108, (1993)

CONFERENCE PRESENTATIONS

9* S. Li, and J. Khurgin "Electroabsorption in type II superlattices" presented at SPIE symposium on Quantum Well and Superlattice Physics, IV Sommerset, NJ Mar 23-24 1992 and published in *"Proceedings of SPIE"*, **1675,** (1992)

10* S. Li, and J. B. Khurgin "Electroabsorption in type II superlattices" presented at CLEO-92, Anaheim CA May 10-15 1992

11* Y. J. Ding, C. L. Guo, S. Li, J. B. Khurgin, K-K Law, J. L. Merz, "Evidence for CW saturation of interface traps in multiple stepped quantum wells", presented at CLEO-92, Anaheim CA May 10-15 1992

12* "Observation of photoluminescence saturation in multiple narrow asymmetric coupled quantum wells" Y. J. Ding, C. L. Guo, J. B. Khurgin, K-K Law, J. L. Merz, presented at QELS -92, Anaheim, CA May 10-15 1992 and published in the QELS -92 digest, p.126

13 Y. J. Ding, C. L. Guo, J. B. Khurgin, K.-K. Law, and J. L. Merz, "Evidence for strong saturation of interface traps in multiple narrow slightly asymmetric coupled quantum wells," 1992 OSA Ann. Meet., Sep. 20-25, 1992, Albuquerque, NM; 1992 Tech. Dig. Ser., vol. 23 (OSA, Washington, DC, 1992), pp. 99, Paper WB4.

14*. "Nonlinear optical properties in IR region in QW's" J. B. Khurgin and S. Li presented at the OSA Quantum Optoelectronics Topical Meeting, Palm Springs, Ca Mar. 17-19 1993 and published in the proceedings, p.22